

## Top physics beyond the LHC

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Several proposals exist for energy-frontier facilities after the HL-LHC. In this contribution I review the potential of these facilities to perform key measurements of top quark properties and interactions. Top quark precision physics at a lepton collider provides excellent opportunities for the determination of the top quark mass and its couplings to neutral electro-weak gauge bosons. Measurements at very high center-of-mass energy at a new hadron collider likely offer the ultimate precision on the QCD interaction of the top quark and its coupling to the Higgs boson. The combination of a lepton and a hadron collider can improve the precision of all these measurements by two orders of magnitude with respect to the current state-of-the-art and by an order of magnitude compared to the precision envisaged after  $3 \text{ ab}^{-1}$  at the LHC.

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# 1 Introduction

In the early 70s, when the top quark was postulated [1], energy-frontier colliders were relatively cheap. A rich programme around the world gave rise to a flurry of discoveries that established the Standard Model of particle physics. In 1995 the observation of the top quark was announced by the experiments operating at the Tevatron [2, 3]. At the same time  $e^+e^-$  colliders at SLAC and CERN could infer the top quark mass from precision measurements. Today, the Large Hadron Collider (LHC) operates at the luminosity and center-of-mass energy it was designed for. It is the only energy-frontier facility in the world and will maintain that position for a good part of its lifetime.

With the discovery of a boson [4, 5] compatible with the predictions for the SM Higgs boson [6], the theory of the electro-weak and strong nuclear interactions is complete. Credible extensions of the Standard Model are under pressure from the null result of a large variety of searches. In this situation there is no obvious target for the next facility of particle physics. We enter an era of exploration, where precise and sensitive measurements of known processes may be the best opportunity to reveal hints of the high-scale physics that lies beyond the Standard Model.

An in-depth scrutiny of top quark production at colliders may uncover such evidence. A precise determination of the top quark mass (together with a precise measurement of the W-boson mass) tests the internal inconsistency of the SM. Precise measurements of the QCD or EW interactions of the top quark have exquisite sensitivity to broad classes of extensions of the SM. A direct and precise measurement of the Yukawa coupling of the top quark tests the Higgs mechanism where its coupling is strongest. Searches for flavour-changing-neutral-current interactions involving top quarks target yet another sector of possible extensions of the SM.

In this contribution I explore the progress new facilities may bring to top quark physics in the post-LHC era. The expectations for the remainder of the LHC programme and its luminosity upgrade are covered in another contribution to these proceedings [7].

In Section 2 the existing projects for energy-frontier facilities are briefly introduced. Sections 3 and 4 provide necessary background information about top quark production at hadron and lepton colliders. In Sections 5 through 9 the prospects for a number of key measurements in top physics are presented. Finally, Section 10 presents a summary and outlook.

## 2 Future collider projects

Accelerating technology has made important progress over the last decades. Where the SLAC linear collider was built with 17 MV/m cavities, the superconducting cavities for the ILC and XFEL reach accelerating gradients of 35 MV/m [8]. The proof-of-principle for drive-beam acceleration has been demonstrated, with a gradient of up to 100 MV/m [9], enabling multi-TeV operation in a relatively compact machine. The last decades have also witnessed steady progress in magnet technology: LHC dipoles produce a bending field of 8 T, a factor two stronger than the magnets used at the Tevatron. Projects for very large hadron colliders, with an energy reach that exceeds that of the LHC by up to a factor 7, rely on the development of 16 T dipole magnets.

Even after successful conclusion of the R&D phase, the lead time for energy frontier facilities (the technical design, political negotiations, construction and commissioning) is measured in decades. If a new facility is to be operational by the end of the LHC programme, construction must start in the early 2020s. The large cost of the next facility of this scale requires coordination at a global level. After the demise of the domestic collider programme in the US and with the long-term commitment of Europe to the LHC programme, Asia is definitely a powerful partner, and possibly the host, of any new large-scale facility. In Table 1 the energy-frontier collider projects are listed.

The complementarity of the lepton collider projects is clear: the circular machines can provide unrivalled luminosity at low energy, but have limited energy reach. For the maximum circumference envisaged (100 km) the top quark pair production threshold can be reached [14]. For  $e^+e^-$  collisions at still higher center-of-mass energy linear colliders are the only viable solution. The linear colliders are the most mature projects. The ILC has finalized the technical design [8] and entered the phase of negotiations between the envisaged host (Japan) and international partners. It is followed closely by CLIC, that has prepared an extensive conceptual design report [9].

An upgrade of the LHC dipoles with 16 T bending magnets in the existing LHC tunnel could roughly double the energy reach. The FCChh and SPPC projects are much more ambitious: a new, circular  $pp$  collider with a size several times that of the LHC should reach up to 100 TeV. Physics and detector studies for the latter two machines are ramping up rapidly. A complete CDR is expected before the update of the European Strategy in 2019.

Table 1: Projects for energy-frontier facilities. Integrated luminosities correspond to different running times (typically ten years per energy point) and are subject to large uncertainties. The last column provides a reference to the most recent design report. References to detailed running scenarios are given where available. All  $e^+e^-$  colliders envisage a brief period of running at energies close to the top quark pair production threshold, that is not listed here.

<b>energy-frontier lepton colliders</b>					
project	host	type	$\sqrt{s}$ [TeV]	$\int \mathcal{L}$ [ab $^{-1}$ ]	status
ILC	Japan	linear $e^+e^-$	0.25 0.5	0.5 (2) 0.5 (4)	TDR 2013 [8] staging [10, 11]
CLIC	CERN	linear $e^+e^-$	0.38 1.5,3	0.5 1.5,2	CDR 2012 [9] staging [12]
CEPC	China	circular $e^+e^-$	0.25	5	CDR 2017 [13]
FCCee	CERN	circular $e^+e^-$	0.25/0.36	10/2.6	CDR < 2019 [14]
$\mu$ collider	FNAL?	racetrack $\mu^+\mu^-$	0.125-3	-	R&D [15]
<b>very-high-energy pp colliders</b>					
project	host	tunnel	$\sqrt{s}$ [TeV]	$\int \mathcal{L}$ [ab $^{-1}$ ]	reference
VLHC	CERN	LEP/LHC	25		-
FCChh	CERN	new	100	20	[16, 17, 18, 19]
SPPC	China	new	70-140	3	[13]

### 3 Top quark production at future hadron colliders

High-energy hadron colliders produce copious samples of top quarks through QCD pair production and EW single top production. Where the Tevatron collected a sample of tens of thousands of top quark pairs, the LHC has produced tens of millions. With the HL-LHC this number will increase by two further orders of magnitude. At a higher-energy machine several further orders of magnitude can be added. An overview of cross sections for Standard Model processes at a 100 TeV pp collider is given in Fig. 1 (a). A proton collider with a center-of-mass energy of 100 TeV and an integrated luminosity of order  $10 \text{ ab}^{-1}$  will produce an astonishing sample of  $10^{12}$  top quark pairs. The increase in rates is even more impressive in the high-mass tail and in associated production of top quarks with gauge bosons or the Higgs boson.

The abundant production of highly boosted top quarks challenges detectors and reconstruction techniques. The decay products from a 5 TeV top quark are typically collimated in an area with  $\Delta R < 0.1$ . Traditional signatures, such as isolated leptons and jet multiplicity are expected to be less distinctive than at the LHC. The detector granularity needed to resolve jet substructure is challenging for in particular of the (hadronic) calorimeter system. Selection of final states with (boosted) top quarks is therefore far from trivial. Several authors have explored approaches to deal with hyperboosted top quarks, using substructure analysis [17], substructure analysis limited to charged particle tracks [20], or even the lepton-in-jet signature [21].

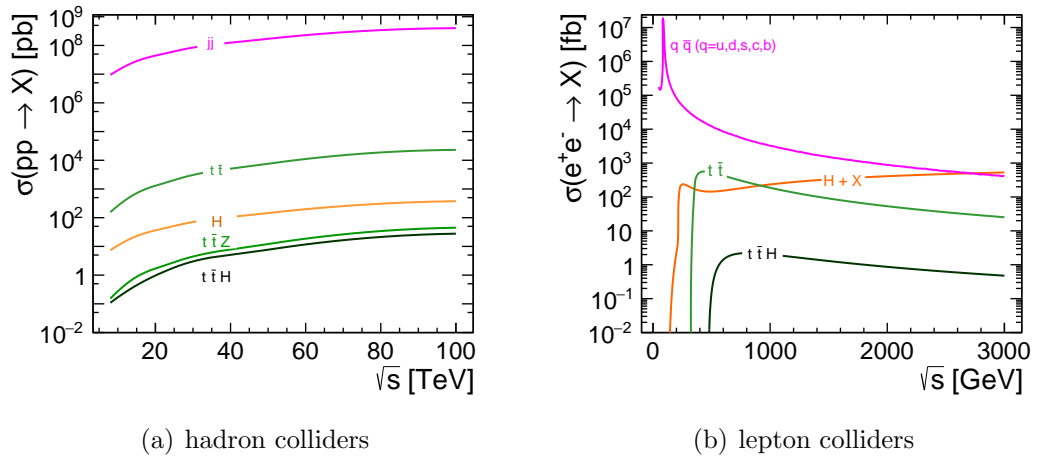


Figure 1: The cross sections for SM processes as a function of center-of-mass energy. In panel (a) the predictions are given for a proton-proton collider with  $8 \text{ TeV} < \sqrt{s} < 100 \text{ TeV}$ . In panel (b) the unpolarized production cross section for  $e^+e^-$  collisions is shown in for center-of-mass energies up to 3 TeV.

As statistical uncertainties become irrelevant even for processes that are rare to-

day, “one of the key obstacles in precision measurements at hadron colliders [...] is the intrinsic difficulty in performing accurate absolute rate predictions [19]. Even today, theory uncertainties exceed the experimental ones for the inclusive  $t\bar{t}$  production cross section. The most precise measurements by ATLAS and CMS have a precision of approximately 4%, (the statistical uncertainty contributing only 0.1%), whereas the theory uncertainty adds up to approximately 5-6% [22]. The ultimate potential of the top physics programme at hadron colliders therefore depends crucially on the ability to reduce systematic uncertainties.

## 4 Top quark production at future lepton colliders

Lepton colliders present a very different environment, where top quarks, and especially background events, are produced at a more modest pace. The cross sections for important SM processes are shown in Fig. 1 (b). At a center-of-mass energy of 500 GeV, close to the maximum rate, the unpolarized cross section is approximately 600 fb, increasing to 1 pb for polarized beams. Even the ILC luminosity upgrade will not produce more than a few million top quark pairs. At higher energy the cross section for the s-channel process drops rapidly (more rapidly than the luminosity increase expected at linear colliders) and production is even less abundant. At lepton colliders cross sections are *democratic*. Top quark pairs are the dominant source of 6-fermion final states, so that no trigger is required and measurements can be very inclusive, with virtually no background.

The key to precision physics at lepton colliders is the possibility to compare per-mil level measurements to equally precise predictions. There is no PDF uncertainty and QCD scale uncertainties are of the order of several per mil. The beam energy, luminosity and polarization can be controlled to 0.1%. From existing full-simulation studies [8, 23, 24] it seems that lepton collider experiments may indeed control the experimental systematics in top quark studies to the required level. However, a detailed study of signal modelling and acceptance uncertainties remains to be performed.

## 5 The top quark mass

The determination of the mass of the heaviest elementary is a key measurement, testing the relations that the Standard Model predicts between the  $W$ -boson mass, the top quark mass and the Higgs boson mass (see, for instance, Ref. [25]) and the stability of the vacuum at large scales [26].

The current world average for the top quark mass based on *direct* measurements at hadron colliders have attained a precision of better than 0.5% [27]. Several single measurements by CMS and D0 achieve 500 MeV uncertainty. After three years of

operation at approximately half the design energy the ATLAS and CMS already exceed the expectations [28] drawn up before the start of the LHC.

Expectations for further progress at the LHC range from a pessimistic 500 MeV [29] after the complete LHC programme to 200 MeV [30]. This uncertainty does not include the ambiguity in the interpretation, that is estimated to be  $\mathcal{O}(1 \text{ GeV})$  [29, 31, 32, 33, 34]. Significant theory progress is required to make sure that the uncertainty in the interpretation of the measurements catches up with experimental progress. A possible avenue is indicated by the method of Ref. [35], that may provide a means to *calibrate* the mass to a field-theoretical mass definition to a precision of several 100 MeV. Given that the theory uncertainty, with an unclear future evolution, is likely to dominate the measurement at hadron colliders the FCChh Standard Model study group prefers not to give prospects for top quark mass measurements [19].

Measurements using alternative methods with complementary sensitivity to the main systematics may reveal a possible tension not covered by the systematic uncertainties. Rigorous pole mass extractions from (differential) cross sections are to reach 1 GeV precision in the near future [36]. Progress beyond this precision will depend on the development on new methods and is therefore unpredictable.

The cross section around the top quark pair production threshold at a lepton collider offers excellent sensitivity to the top quark mass [42]. The shape can be predicted to good precision using a NNNLO NRQCD calculation [43]. The effect of Initial-State-Radiation, beam energy spread and beamstrahlung modify this shape somewhat, introducing slight differences between  $e^+e^-$  collider projects. A fit to a ten-point threshold scan with a total integrated luminosity of  $100 \text{ fb}^{-1}$  yields a statistical precision on a threshold mass (the 1S or PS mass) of approximately 20 MeV. The dominant uncertainty on the top quark mass extraction is expected to be due to the theory uncertainty, in the prediction of the line shape [40] and the conversion to a short-distance mass [44] (such as the  $\overline{MS}$  mass). Provided the strong coupling

Table 2: Brief summary of the prospects for the precision of the top quark mass measurement at different facilities. HL-LHC prospects are based on Ref. [30]. The experimental precision in an  $e^+e^-$  threshold scan is based on Refs. [37, 38, 39] and the theory uncertainties on Refs. [40, 41].

top quark mass prospects			
project	$\sqrt{s}$ [TeV]	$\int \mathcal{L}$ [ab $^{-1}$ ]	precision [MeV]
Tev + LHC8	$1.96 + 8$	$0.01 + 0.02$	$500 \text{ (exp.)} \oplus 1000 \text{ (theo.)}$
HL-LHC	14	3	$200 \text{ (exp.)} \oplus ? \text{ (theo.)}$
$e^+e^-$ collider	0.35	0.1	$20 \text{ (exp.)} \oplus 50 \text{ (theo.)}$
new $pp$ collider	100	20	? (theo.)

constant  $\alpha_s$  is known to sufficient precision the total theory uncertainty amounts to approximately 50 MeV. The prospects for the top quark mass measurement of HL-LHC, lepton colliders and a future high-energy  $pp$  collider are summarized in Tab. 2.

## 6 Top quark QCD couplings

The QCD interactions of the top quark are already tightly constrained by measurements at the Tevatron and the LHC. A fit to all existing data provides limits on the Wilson coefficients of dimension-six operators affecting the  $t\bar{t}g$  vertex and the  $q\bar{q} \rightarrow t\bar{t}$  four-fermion operators that are order  $0.1 \times \Lambda^2/v^2$  [45, 46]. Measurements in extreme corners of phase space, where top quarks are highly boosted and new techniques are required, provide constraints of comparable strength to the more classical analyses [47]. In the future such measurements are expected to become much more precise. With their much enhanced sensitivity to the effect of new physics at high scales the constraints can be substantially improved [48].

The potential of lepton colliders to constrain anomalous chromo-magnetic moments was studied in Ref. [49], with results that are competitive compared to the HL-LHC prospects.

The SPPC or FCChh are to take measurements on  $t\bar{t}$  production well beyond the energy reach of the LHC. Ref. [21] envisages the extraction of top-quark chromo-electric and chromo-magnetic moments from a measurement of the cross section with  $m_{t\bar{t}} > 10$  TeV. Even with pessimistic assumptions on the ability of the experiments to isolate highly boosted final states and a 5% systematic uncertainty such a measurement can improve the HL-LHC constraints by an order of magnitude. The prospects for constraints on the top quark QCD interactions are summarized in Tab. 3.

Table 3: Brief summary of the prospects for the precision of constraints on the top quark QCD interactions at different facilities. The expected 95% C.L. limits on  $d_V$  and  $d_A$  for the Tevatron + LHC8, LHC14 and FCChh are taken from Ref. [21]. The expected precision at lepton colliders is based on the old study of Ref. [49].

top quark QCD coupling prospects ( $d_V, d_A$ )			
project	$\sqrt{s}$ [TeV]	$\int \mathcal{L}$ [fb $^{-1}$ ]	expected precision
Tev + LHC8	$1.96 + 8$	$0.01 + 0.02$	$ d_V  < 0.02,  d_A  < 0.09$
LHC	14	0.3	$ d_V  < 0.01,  d_A  < 0.02$
$e^+e^-$ collider	possibly competitive with HL-LHC at 1 TeV		
new $pp$ collider	100	20	$ d_V ,  d_A  < 0.003$



## 7 The top quark and the Higgs boson

A direct measurement of the interaction of the top quark and the Higgs boson - with a unit Yukawa coupling - is a priority in high energy physics. ATLAS and CMS have some evidence that associated  $t\bar{t}H$  production indeed occurs and have  $\mathcal{O}$  (100%) uncertainty on the production rate. The precision of the measurement Yukawa coupling is expected to reach  $\mathcal{O}$  (10%) at the end of the complete HL-LHC programme [50].

The  $t\bar{t}H$  final state is produced at lepton colliders. The cross section shows a sharp turn on at around 500 GeV and reaches a broad maximum of 2 fb at about 800 GeV. Full-simulation studies have been performed at several center-of-mass energies between 0.55 TeV and 1.5 TeV. The top quark Yukawa coupling can be determined to 3-4% precision in this interval [51, 10, 52] with the integrated luminosities envisaged for the ILC and CLIC.

At a 100 TeV hadron collider the  $t\bar{t}H$  production cross section is over 30 pb. The (NLO) theory uncertainty on the predicted rate is approximately 10%, dominated by scale uncertainties. Ref. [53] shows that in the ratio of rates for two closely related associated production processes,  $t\bar{t}H$  and  $t\bar{t}Z$ , the uncertainty is reduced to 1-2%. The robustness of uncertainty estimate based on the (synchronous) variation of the renormalization and factorization scales in ratios of cross sections can be tested at the LHC (cf. the ATLAS measurement of the ratio of the  $t\bar{t}$  cross sections at 7 TeV and 8 TeV [54] or the ratio of top and Z cross sections [55]). A phenomenological study of mildly boosted  $t\bar{t}H$  events in the same paper predicts that an extraction of the Yukawa coupling to 1% precision is feasible. While a detailed experimental study is still lacking, it is clear that a high-energy hadron collider is the only machine on the horizon with the potential to reach this precision. The prospects of all future facilities are summarized in Tab. 4.

Table 4: Brief summary of the prospects for the precision of measurements of the top quark Yukawa coupling at different facilities. HL-LHC prospects are taken from Ref. [50]. The expected precision at a linear lepton colliders incorporates the results of several ILC and CLIC studies at center-of-mass energies ranging from 0.55-1.5 TeV and assumed integrated luminosities ranging from 1-4  $\text{ab}^{-1}$  [10, 51, 52]. FCChh prospects are taken from Ref. [53].

top quark Yukawa coupling prospects			
project	$\sqrt{s}$ [TeV]	$\int \mathcal{L}$ [ $\text{ab}^{-1}$ ]	expected precision
HL-LHC	14 TeV	3	10%
$e^+e^-$ collider	0.55-1.5 TeV	1-4	3-4%
$pp$ collider	100 TeV	10-20	1%

## 8 Top quark FCNC interactions

Flavour changing neutral current (FCNC) interactions involving top quarks are suppressed to well below detectable levels in the Standard Model, but can reveal sizeable contributions from a variety of new physics setups. The limits on the strength of the  $tq\gamma$ ,  $tqZ$ ,  $tqH$  and  $tqg$  vertices from LEP, HERA and the Tevatron are rapidly being superseded by LHC searches for rare top decays [56].

Future lepton colliders may probe FCNC interactions in top quark production through  $e^+e^- \rightarrow tj$  production [57] or in decays [58]. With the relatively small top quark pair production rate compared to hadron colliders, the latter is competitive primarily for channels that are particularly challenging at the LHC. An example is  $t \rightarrow cH$  that can be constrained to  $BR \sim 10^{-5}$  by the ILC at  $\sqrt{s} = 500$  GeV [58], compared to  $BR \sim 10^{-4}$  for the HL-LHC programme [59].

Hadron colliders at  $\sqrt{s} = 100$  TeV produce billions of top quark and can potentially limit the branching ratios for rare top quark decays such as  $t \rightarrow q\gamma$  and  $tqZ$  to the  $10^{-7}$  level (two orders better than HL-LHC). Dedicated studies are missing, however, and Ref. [19] warns that “the systematic uncertainties in the background predictions will likely be dominant, and a more reliable estimation of the sensitivity requires a detailed analysis. A brief summary of the FCNC prospects of the different projects is presented in Tab. 5.

Table 5: Brief summary of the prospects for the precision of measurements of the top quark Yukawa coupling at different facilities. HL-LHC prospects are taken from Ref. [50], with more recent additions from Ref. [60]. The expected precision at a linear lepton collider is studied in Ref. [24, 58]. A discussion of the potential of the FCC is found in Ref. [19]

top quark FCNC interaction prospects			
project	$\sqrt{s}$ [TeV]	$\int \mathcal{L}$ [ab $^{-1}$ ]	expected precision
HL-LHC	14 TeV	3	$BR(t \rightarrow qX) \sim 10^{-5} - 10^{-4}$
$e^+e^-$ collider	0.5 TeV	4	$BR(t \rightarrow cH) \sim 10^{-5}$
$pp$ collider	100 TeV	10-20	possibly $BR(t \rightarrow qX) \sim 10^{-7}$

## 9 Top quark EW couplings

The EW couplings of the top quark, in particular those involving neutral gauge bosons, are among the least constrained parameters of the Standard Model. Models with a new strong sector (Randall Sundrum, composite Higgs) tend to predict large deviations from the SM predictions [61].

The HL-LHC can constrain the  $t\bar{t}\gamma$  and  $t\bar{t}Z$  vertices directly by studying associated production. In run I these processes were observed and the production cross sections measured to  $\mathcal{O}$  (30%). Measurements of the  $Wtb$ -vertex from studies of top quark decay and single top production can be used to derive constraints on the same operators in an EFT analysis [45].

The relatively rare associated production processes benefit strongly from an increase in the center-of-mass energy, with statistical uncertainties becoming irrelevant. Recent studies [62, 63] show that the (NLO) theory uncertainty can largely be circumvented by forming the ratio of  $t\bar{t}X/t\bar{t}$ , where  $X$  is a  $Z$ -boson or a photon. A simultaneous measurement of both ratios strongly improves the limits on EW magnetic and electric dipole moments.

Future lepton colliders with sufficient energy to produce top quark pairs are the natural place to study  $t\bar{t}\gamma$  and  $t\bar{t}Z$  vertices [64, 65, 66, 67]. Constraints on the form factors reach sub-% precision, one to two orders beyond the prospects of the HL-LHC and well beyond the reach of even a 100 TeV hadron collider.

Table 6: Brief summary of the prospects for the precision of constraints on the top quark QCD interactions at different facilities. Results are presented as expected 68% C.L. limits on the form factors of the  $t\bar{t}Z$  vertex. The expected precision at HL-LHC is based on Ref. [68], that at lepton colliders on Ref. [65].

top quark EW coupling prospects ( $F_{1V}, F_{2V}, F_{1A}, F_{2A}$ )			
project	$\sqrt{s}$ [TeV]	$\int \mathcal{L}$ [ab $^{-1}$ ]	expected precision
HL-LHC	14 TeV	300 fb $^{-1}$	$\sim 0.03$ -0.2
$pp$ collider	100 TeV	10-20 ab $^{-1}$	factor 3-10 wrt HL-LHC
$e^+e^-$ collider	0.5 TeV	500 fb $^{-1}$	$\sim 0.002$ -0.005

## 10 Summary and outlook

New energy-frontier facilities offer new opportunities for top physics in the post-LHC era. In this contribution I have reviewed the potential of future lepton and hadron colliders, with a focus on measurements with exquisite BSM sensitivity.

An  $e^+e^-$  collider with a center-of-mass energy exceeding  $2m_t$  enables the scrutiny of the top quark in a precision environment. An energy scan through the top quark pair production threshold can realistically yield a determination of the  $\overline{MS}$  mass to 50 MeV. The comparison of per-mil-level measurements with equally precise SM predictions provides constraints on the  $t\bar{t}Z$  and  $t\bar{t}\gamma$  vertices that are an order of magnitude more stringent than those expected at the HL-LHC, indirectly probing new physics scales in excess of 10 TeV. A direct measurement of the top quark Yukawa

coupling in associated  $t\bar{t}H$  production can be performed to a precision of 3-4% at (linear) colliders with a center-of-mass energy exceeding 550 GeV.

A very large hadron collider, with a center-of-mass energy up to 100 TeV, will extend the mass reach of direct searches and provide very tight constraints on the QCD interactions of the top quark. The FCChh has the potential to measure the top quark Yukawa coupling to 1% precision. In many areas, such as the top quark mass measurement and searches for FCNC decays such a machine has clear potential to go well beyond the state-of-the-art in 2037, but thorough studies are yet to be performed.

Much work remains to be done to establish a complete picture of the top quark physics potential of different facilities. Many new studies are expected to appear before the European strategy update, that is to conclude in the first half of 2020. Progress in theory and new results at the LHC may tell us what level of control to expect over systematic uncertainties from the construction of carefully chosen cross-section ratios. The emerging global EFT analyses can provide a valuable tool to interpret the BSM sensitivity of measurements in different processes, at different energy and with different precision.

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